ADVANCED ASPIRATING SEAL

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Advanced Aspirating Seal

Stein Seal Company

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Stein Seal Company is developing and testing an improved 14.7” aspirating seal for GE gas turbine compressor discharge applications. The aspirating seal provides hydrostatic operation with low leakage and high gas film stiffness at high differential pressures and high temperatures. This all metal seal has the ability to operate at high temperature with large rotor runout. The design process and comparison to the original aspirating seal will be discussed along with recent test data.

Advanced Aspirating Seal

Outline

- Design Goals & Operating Conditions
- Seal Operation & Evolution
- Analysis - Original & Advanced Seal Design
- Rig Test Results
- Performance Attained

Goals / Objectives

- Develop Advanced Aspirating Seal (IHPTET / JSF Engine)
  - 14.7” & 36” seal
- Meet Leakage and Performance Goals
- Increase Gas Film Stiffness
- Increase Seal’s Ability to Follow Extreme Rotor Runouts
- Increase Seal Operating Speed
- Build & Test 14.7” Seal

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The advanced aspirating seal is being developed by Stein Seal Company for GE Aircraft Engine. The advanced seal offers improvements beyond the original aspirating seal design built several years ago.

Two seal sizes were studied and include a 14.7” seal and a 36” seal. The 14.7” seal was built and tested. The 36” seal was designed but not built.

The topics for discussion and program goals/objectives are included above.

Advanced Aspirating Seal

Requirements / Challenges / Application

Operating Conditions:

- Shaft Speed: 365 ft./sec.
- Press. Diff.: 100 psid
- Air Temp.: 750 ºF
- Leakage: ~ 1.25 scfm/psid
- Seal Life: Unlimited (non-contacting seal)

Applications:

- Turbine Rim Seal
- Compressor Discharge

Challenges:

- Improve gas film stiffness
- Maintain uniform gas film clearance during all conditions
- Maintain low leakage performance
- Provide infinite seal life
- All metal design

Funding:

- Provided by GE Aircraft Engine
  - Developed under NASA's AST program (Glenn Research Center)
    - » IHPTET initiative

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The operating conditions are shown and are representative for the 36" seal.

The seal is developed under NASA's AST program and funded by GE Aircraft Engine (Cincinnati)

The advanced seal requires an improvement to the gas film stiffness as compared to the original seal. Low leakage and uniform gas film clearance are requirements for the all metal seal design.

The advanced aspirating seal is targeted for Turbine rim seal and Compressor discharge applications. The aspirating seal is a replacement for brush seals and has significant leakage improvement as compared to brush seals. The aspirating seal leakage is approximately 20% of a brush seal.

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Aspirating Seal Evolution

1989 - 1996

Original Aspirating Seal

- 14.7” (Tested at Stein)
  - .400” air bearing
  - .100” dam
  - .150” trench
- 36” (Tested at GE CRD)
  - .440” air bearing
  - .100” dam
  - .160” trench

1996 -1999

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- 14.7” (Tested at Stein)
  - 1.25” air bearing
  - .250” dam
  - .450” trench
- 36” (Analysis performed)
  - .550” air bearing
  - .050” dam
  - .180” trench

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This slide shows the physical parameters for the aspirating seal that have been developed during the last ten years.

The original seal designs are characterized by narrow seal dams and narrow air bearing faces. The advanced aspirating seal has wide seal dams and wide air bearing faces. This yields improvements to the gas film stiffness.

The trench area is an annulus that separates the seal dam from the air bearing.

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Development Efforts
Two Seal Sizes Developed:

Sub-Scale Seal

- 14.7” Seal (Rig Seal)
  - Optimized design
  - For rig testing at Stein
  - Utilizes highest gas film stiffness within GE-90 rotor envelope
- Rotor flow diverter <u>not required</u>

Full Size Seal

- 36” Seal (Paper study)
  - Seal targeted for GE CRD test rig
  - Utilizes existing rig rotor with changes
- Rotor flow diverter <u>is required</u>

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<u>14.7” seal</u>

This seal has the widest face configuration that fits the GE-90 rotor envelope. The gas film stiffness is greatly improved compared to the original aspirating seal. This seal configuration was chosen for rig tests due to the performance increase.

The flow diverted is not required on the rotor.

<u>36” seal</u>

This seal has a radial face configuration that fits the existing rig rotor face on the GE CRD rig. This seal was developed to demonstrate that an improved aspirating seal could be developed to fit an existing test rig. This seal , to date, has not been built.

<u>Rotor flow diverter</u>

The rotor diverter is a piece of the rotor that projects into the trench (annulus) between the seal dam and air bearing. Although the rotor flow diveter is not required on the 14.7” seal, the flow diverter operation directs the seal dam gas flow into the radial and axial vent slots. Without the rotor flow diverter the seal may have a tendency to not establish the proper gas film since air from the seal dam discharge tends to exit radially and disrupt the gas flow on the air bearing.

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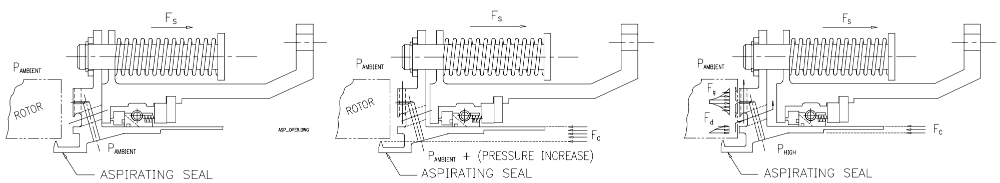
Seal Operation

Force Balance Equation, Fc = Fg + Fd + Fs + Inertia + Friction



START-UP / SHUT-DOWN: (0 PSID)

- Seal is retracted open by springs
- Gap exists between seal and rotor face

AT PRESSURE INCREASE: (< 5 PSID)

- Seal is still retracted open by springs
- Pressure increases and seal starts to close towards rotor.
    - Pressure drop occurs across balance dia. and laby tooth
    - Closing force overcomes retraction spring and friction forces
- Gap between rotor and seal face decreases

WITH PRESSURE DIFFERENTIAL: (> 5 PSID)

- Seal moves toward rotor as pressure continues to build
    - Retraction spring force, friction force, and inertia forces are overcome
- As seal approaches rotor
    - Pressure drop occurs across seal dam
    - Air bearing force is established
- Laby tooth is no longer the primary pressure breakdown mechanism
- Seal is in equilibrium (1.5 to 2.0 mils gap)
    - Closing forces = Opening forces

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The seal operation is characterized by a non-contacting seal.

Start up / Shut down:

At rest, the seal is retracted open by springs. This pulls the seal away from the rotor. At this position the seal has no pressure drop across the seal.

At pressure build up:

As pressure builds, the closing force starts to increase, overcoming the retraction spring forces and the friction and inertia forces. The pressure force is established by the area created by the balance diameter and the laby tooth (located beneath the rotor.)

At full pressure:

The seal is in equilibrium at 1.5 top 2.0 mils. The closing force equals the opening force. The closing force is established by the area created by the balance diameter and the seal dam ID. The opening force is created by the air bearing force. This force tends to open the seal.

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Work Performed

- Parametric Studies
  - Studied seal performance effects with varied seal features:
    - » Seal dam, gas bearing, & trench geometry
- Gas Bearing Analysis & Rig Tests
  - Analysis performed by Wilbur Shapiro, Inc.
    - » NASA GFACE Code
  - Rig tests validated analysis
- Optimized Design Features:
  - 36" Seal: .550" gas bearing, .050" dam, .180"trench
  - 14.7" Seal: 1.250" gas bearing, .250" dam, .450" trench
- CFD Analysis (CFDRC Corp.)
  - Performed on 14.7" & 36" seals
    - » 14.7" Seal: Rotor flow diverter not required
    - » 36" Seal: Rotor flow diverter required
    - » Operating Gap: .0015" to .0020"

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Parametric design studies looked at all possible seal configurations that would show improve d performance as compared to the original aspirating seal. Features that affect seal performance include:

Size and placement of the seal dam and air bearing

Number of air bearing holes, hole diameter, and number of rows of holes, and hole spacing

Gas bearing analysis and static rig tests were performed to determine the gas bearing performance. The actual rig tests were used to correlate the NASA GFACE seal code and Coefficient of Discharge, Cd.

The optimized seal configurations for both seal sizes are shown. The 14.7" seal has the widest radial face as it has the optimum gas bearing stiffness per unit length. The 36" seal fits the existing rig rotor at GE CRD.

Computational Fluid Dynamics (CFD) was performed on both seal sizes. CFDRC of Huntsville, Alabama, performed these studies. Conclusions showed that the rotor flow diverter was required on the 36: seal but not required on the 14.7' seal. The seals operate properly with a gas film of 1.5 to 2 mils.

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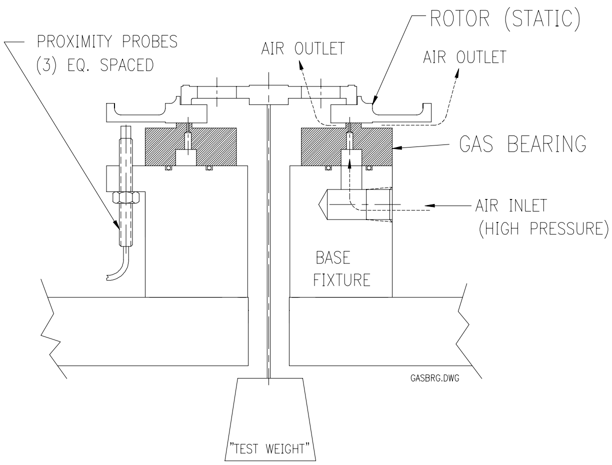
Static Gas Bearing Rig



- Provides data for Pressure vs.:
  - Load capacity
  - Film clearance
  - Leakage
- Data used to validate NASA GFACE code
- Static rig permits quick bearing change-outs for alternate bearing faces:
  - Multiple orifice rows
  - Orifice hole size and spacing

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Static gas bearing test rig for sub-scale testing.

The rig is used to collect information such as:

Leakage vs. pressure

Film clearance vs. pressure

Proximity probes measure the gas film clearance.

Gas flow in inward. The test weight simulates the seal closing force at the rated pressure differential.

The data form this test rig is used to correlate the NASA GFACE seal code.

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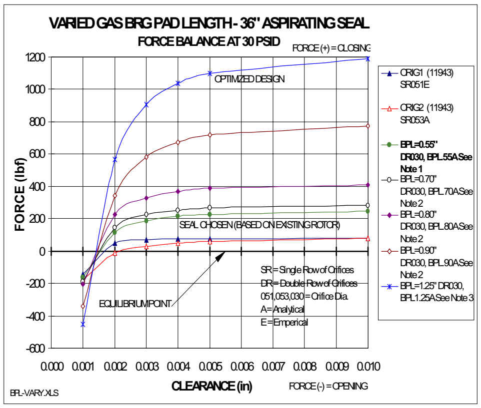
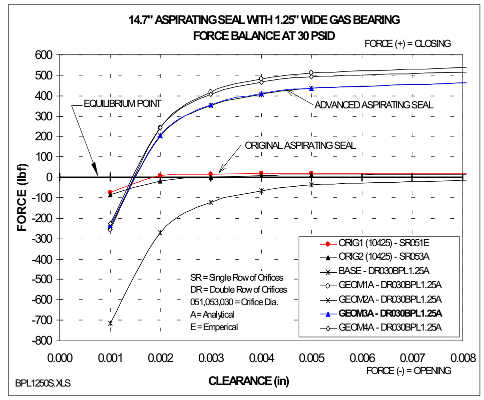
Analysis - Force vs. Clearance

14.7” & 36 “ Seals





- Advanced seal has steep slope at equilibrium point for:
  - Slope vs. Clearance
- Original seal has shallow slope
- Steep slope yields improved gas film stiffness

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Aspirating seal operates at an equilibrium point where the gas film is maintained at 1.5 to 2.0 mils.

Seal equilibrium point is where Force = 0 lbf. on the Y-axis. The operating gas film clearance is determined where the curve line cross the equilibrium point.

Steep line slopes are desirable since any change in clearance is a correspondingly high change in force.

The original aspirating seal configuration (solid circle) has a less steep slope as compared to the improved aspirating seal configuration (open triangle).

Gas bearing face width comparison:

.440” Original aspirating seal design

1.250” Improved aspirating seal design

Gas film stiffness improvements are gained compared to the original seal design:

14.7” seal: 5.5 : 1 greater stiffness vs. original seal

36” seal: 1.7 : 1 greater stiffness vs. original seal (dictated by rotor size)

36” seal (optimized design): 6 : 1 greater stiffness vs. original seal

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Analysis - Air Bearing Stiffness Comparison

- Improved Gas Film Stiffness (based on 30 psid)
  - 14.7” Advanced Seal Stiffness 5.48 > Original Seal
  - 36” Improved Seal Stiffness 1.67 > Original seal
    - » Seal fits existing rig rotor face
  - 36” Advanced Seal Stiffness 6.02 > Original seal
    - » Optimized design
- Improved Seal Stiffness Benefits:
  - Permits seal to follow extreme rotor runouts
  - Improved load support
  - Small film clearance changes yield larger “righting” force balance

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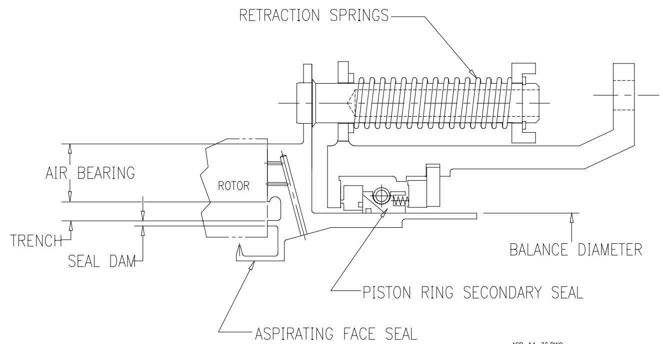
Seal Dimensions - 14.7” & 36”



DIMENSION	SEAL SIZE	
	14.7"	36"
AIR BEARING WIDTH	1.250"	.550"
TRENCH	.450	.180"
SEAL DAM	.250"	.050"
BALANCE DIAMETER	14.700"	36.160"
ORIFICE DIA	.030"	.030"
ORIFICE SPACING	.828"	.806"
NUMBER OF ROWS	2	2

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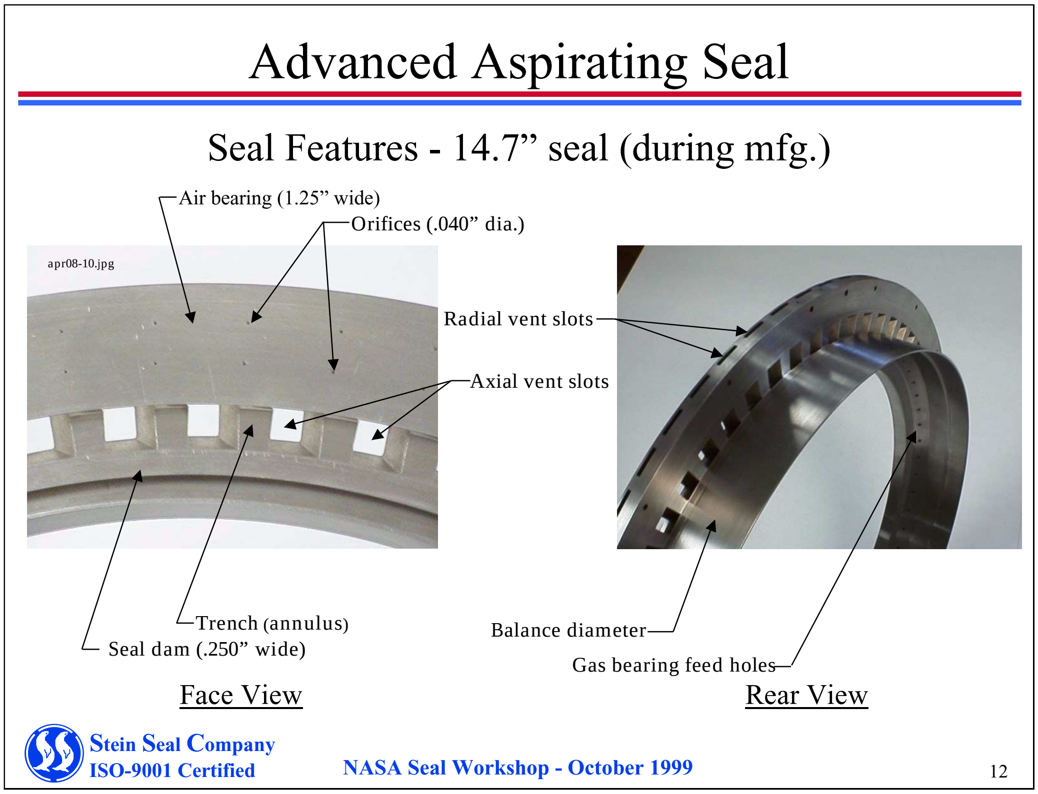
Physical comparison between the 14.7” and 36” aspirating seals.

The balance diameter defines the nominal seal size.

The gas bearing for the 14.7” seal offers the best gas film stiffness improvement as compared to the original aspirating seal.

The gas bearing for the 36” seal is the best size that fits the existing test t rig rotor at the GE CRD facility. If space permitted a larger rotor, then a wider gas bearing face would be utilized.

Each seal has a double row of gas bearing orifices for optimum gas film stiffness for the space permitted.



The photographs show the 14.7” aspirating seal features.(taken during fabrication)

Material: 410 stainless steel

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Rig Tests

1. Gas Bearing Static Tests
2. Gas Film Calibration / Verification
   – Assess bearing supply pressure to orifice
   – Establish film clearance at operating pressure
3. Performance Mapping
   – Static/Dynamic tests
   – Speed and Pressure traverses
4. Rotor Runout Tests
   – 5 mil & 10 mil rotor (one per rev)
5. Max Conditions
   – GE-90 Conditions
6. Sand Ingestion
   – 0 to 10 micron particle size, 1/3000 lb/sec flow rate

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A series of rig tests are planned to assess the seal performance at engine conditions.

Rig tests for the 14.7' seal are performed on a dynamic test rig at Stein Seal Company.

Gas film calibration tests are used to assess the leakage performance with fixed film clearances between the rotor and seal face. Clearances are achieved by the use of shim stock material that is cemented to the rotor face at equidistant positions.

Rotor runout tests are performed to simulate gas turbine rotor whirl on a "one per rev" cycle.

Proximity probes measure the gas film clearance.

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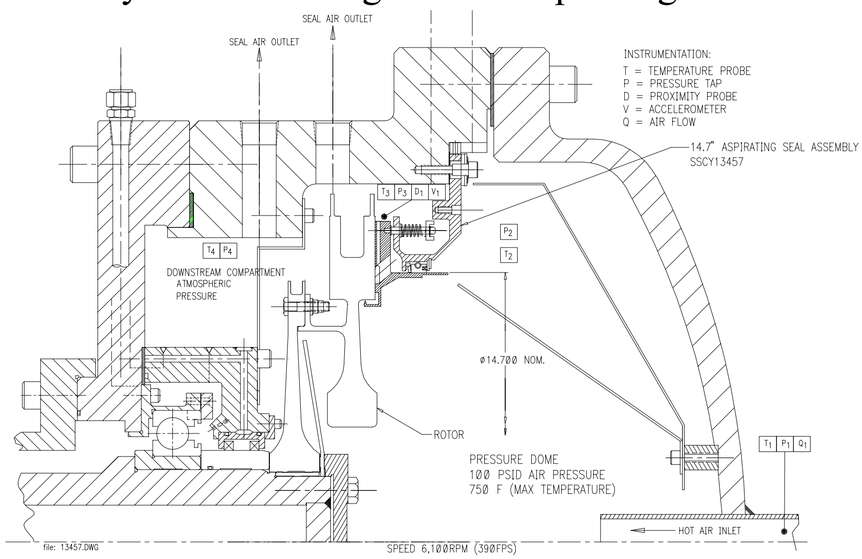
Dynamic Test Rig - 14.7” Aspirating Seal



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Dynamic test rig for the 14.7” sub-scale seal.

During operation the high pressure air enters the rig pressure dome through the air inlet pipe at the far right side. At 0 psid the seal is retracted open by mechanical springs, pulling the seal away from the rotor leaving a .090” gap. As pressure builds to approximately 3 to 4 psid, the seal is aspirated closed towards the rotor, overcoming the retraction spring force and piston ring friction force. The gas film is established between the rotor and seal face; 1 to 2 mils.

The mechanism to close the seal is a pressure force developed by the area projected by the balance diameter and laby tooth diameter.

<u>Test conditions:</u>

Shaft speed: 6,100 rpm (390 fps)

Pressure differential: 100 psid

Temperature (max.): 750 ^{0}F

<u>Seal configuration:</u>

.250” wide seal dam

1.250” wide gas bearing

(2) rows of .030” dia. orifices

.450” wide trench (annulus between the seal dam and air bearing)

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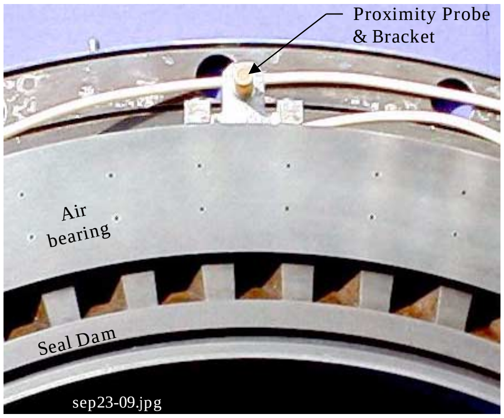
Instrumented Seal - 14.7” seal



Seal Face View

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This photograph shows the seal instrumented with a proximity probe. The probe is mounted on a bracket that is attached to the OD of the seal. The probe is aimed at the rotor face in the dynamic test rig.

The view is looking at the sealing face.

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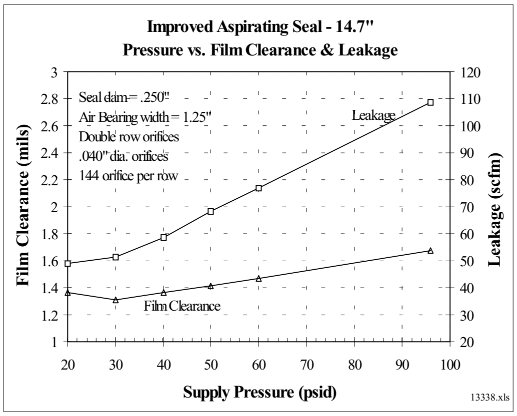
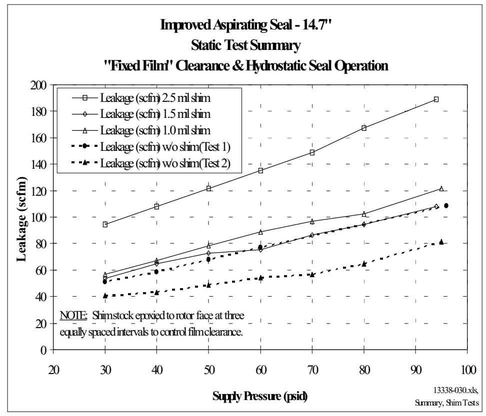
Static Test Results





Initial Test Results:

- Leakage ~ 1.15 scfm/psid
- Film gap = 1.6 mils @ 95 psid

Fixed Film Clearance Test Results:

- Clearance between Rotor & Seal Faces set with shim stock
- Prox probes measurements agree with shim calibration.

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The two graphs represent seal performance on the dynamic test rig. Leakages include the primary face seal and the piston rig secondary seal.

Both graphs represent Pressure Differential vs. Seal leakage.

The graph on the left shows that the gas film clearance is approximately 1.6 mils at 95 psid.

The graph on the right shows the leakage for the “fixed film” clearance tests. The solid lines represent the “fixed film” performance, while the dotted lines represent the seal performance allowing the seal to float at its equilibrium point. In this graph, the film clearance is slightly less than 1 mil, running parallel to the 1 mil “fixed film“ clearance test curve.

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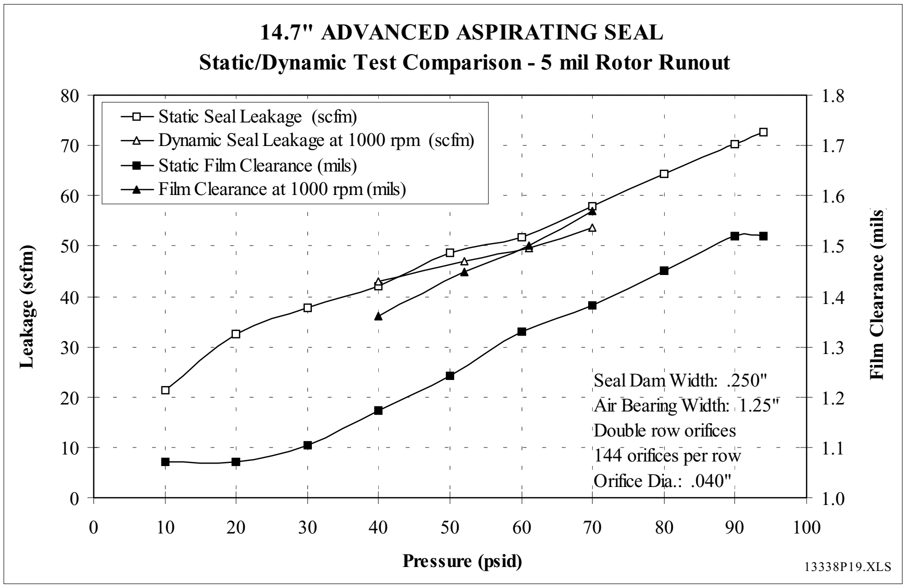

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This graph depicts the static and dynamic seal performance for Pressure vs. Leakage and Film clearance. The shaft speed for the dynamic test was 1,000 rpm (65 ft./sec.)

Leakage and film clearance are closely matched for static and dynamic test conditions.

The rotor face runout during the dynamic test was 5 mils.

The results of the test demonstrate that the seal performance is very close to the analysis for film clearance measurements.

Test: 1.6 mils (static test @ 30 psid), 1.4 mils (dynamic @ 30 psid & 1,000 rpm)

Analysis: ~ 1.5 mils (30 psid)

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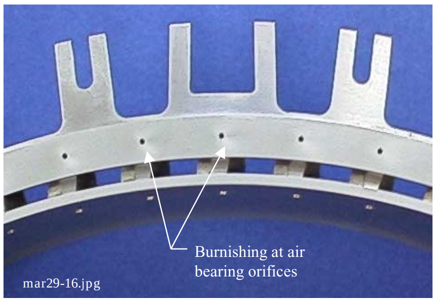
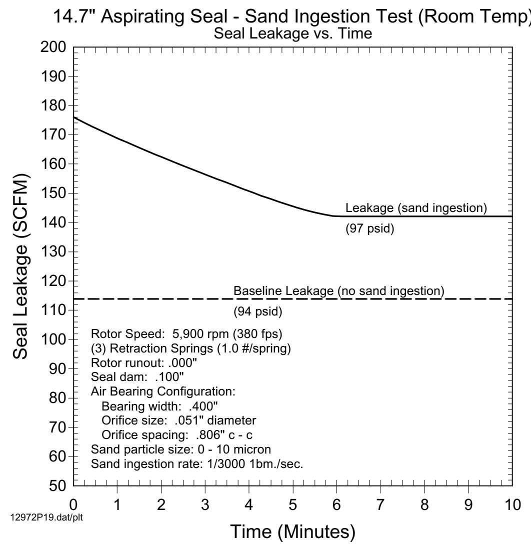
Sand Ingestion Test - Original Aspirating Seal



Original Seal - "After Sand Ingestion"

- •Sand delivered at:
  - •1/3000 lb./sec., 97 psid
  - •10 micron particle size
- •No measurable damage to seal or rotor



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This slide is for reference. The sand ingestion was performed on the original seal with good results.

The sand was delivered into the test head for ten minutes at 1/3000 lbm/sec at 97 psid pressure differential.

The leakage at the onset of sand was approximately 54% higher than the leakage for a test without sand ingestion. As time passed, the leakage settled lower to approximately 24% higher than a seal without sand ingestion.

No damage was noted to the seal faces or orifice holes. It is noted that burnishing did occur near the orifice holes and on the rotor face. Slight burnishing appeared on the seal dam.

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Current Conclusions

- Seal operated successfully to:
  - 65 ft/sec (goal: 365 ft/sec)
  - 96 psid* (goal: 100 psid)
  - Room temp. (goal: 750 ^{o}F)
  - 5 mil Runout (goal: 10 mil)
- Seal performance is predictable
  - Stein analysis & validation tests agree
  - CFD analysis correlates computer codes & test data
  - NASA GFACE code correlates seal interface performance & provided additional information
- Tests are continuing

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Seal performance is predictable and validates the seal codes employed in the aspirating seal design. CFD is a valuable tool in the design of the aspirating seal to determine if the rotor flow diverrter is required. CFD correlated the Stein and NASA GFACE seal codes.

Further tests are required to fully prove the performance during all engine conditions.

The aspirating seal is an ideal alternative or replacement to brush seals operating in high pressure, high temperature conditions. The aspirating seal leakage is an order of magnitude less than the brush seal. The aspirating seal life can be infinite due to its non-contacting performance.

Rig tests are continuing are are necessary to further prove the success of the aspirating seal.